

AN AHP/GM-BASED QUANTITATIVE METHOD FOR DYNAMIC RISK ASSESSMENT OF DEBRIS-FLOW HAZARDS

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ABSTRACT

An innovative quantitative approach for dynamic risk assessment of debris-flow hazards using the integrated skills of analytical hierarchy process (AHP) and grey modeling theory (GM) is developed and verified with a real case occurred in Taiwan. Theoretical model of AHP is first built for risk assessment of debris-flow hazards where 9 important influence factors considering topological, metrological and rain-fall conditions are selected and their relative risk impacts are analyzed. Among these 9 influence factors the GM(1,1) models are employed for intensity of rainfall and accumulated rainfall while linear model is employed for duration of rainfall for prediction. Two predicted schemes are proposed: (1) Single-step prediction (SSP) scheme, and (2) Recycling point-wise prediction (RPP) scheme. The real case of debris-flow disasters occurred Taiwan is tested by the use of AHP/GM: the debris-flow occurred in Tung-Men village, Hua-lien, June 23, 1990. The results show that the proposed AHP/GM integrated quantitative dynamic risk assessment schemes can provide early precaution, warning and alarming in time for the occurrence of debris flow disaster. Using appropriate grey modeling for dynamic influence factors as well as AHP framework and criteria can successfully predict the risk change of debris-flow hazards.

KEYWORD: Debris-Flows, Analytical Hierarchy Process (AHP), Grey Modeling (GM), Grey Prediction, Dynamic Risk Assessment

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INTRODUCTION

Debris flow disasters caused a lot of loss of human beings and property in many countries for a long time. Occurrence of debris flow depends highly on local topographic, meteorologic, geologic, and hydrologic conditions (Takahashi, 1991). Many disasters caused by stony and muddy flows in Taiwan were reported and studied (Jan and Shen, 1993; Wu, et al. 2006; Lin, 2006). The special reasons that Taiwan is prone to debris-flow hazards have also been reported (Jan, 2000; Huang, 2001). Debris flows are inherently dynamically developing temporarily and/or spatially (Peng, 2015).

Scientists and engineers continuously search for appropriate methods and systems for precaution, warning and alarming of the occurrence of debris flows. Huang (2014) has reviewed the research work on debris flow mechanisms and the risk assessment studies in the past in Taiwan. Among these studies some of techniques based on artificial intelligence have been proposed such as application of probability theory (Chen and Jan, 2000), intelligent control theory (Chang and Lee, 1997), expert systems (Lin, 2000), grey relation analysis (Wu, 2002), fuzzy reasoning system Chen (2006) and case-based system (Tsai, 2007). However, most of these assessment techniques consider only a few influence factors and may be not suitable for correct prediction debris-flow hazards including multiple influence factors.

Risk assessment task is a multi-level and multi-criteria complicated process. In the field of operational research, Saaty, T. L. (1980) had proposed the so-called Analytic Hierarchy Process (AHP) for multiple criteria decision making problems. It is also a good approach for risk assessment of problem with multi-criteria on influence factors. The author also had attempted applied AHP to risk assessment of debris-flow hazards occurred in Sen-Mu and Hua-San (Huang, 2014) and Tung-Men and Tung-Shing (Huang, et al. 2015), respectively, and the results are verified to be useful.

Since 1982 Deng proposed the concept of grey system for analysis (Deng, 1989), researches and applications of grey system theory to forecasting and prediction of power load (Tamura, et al. 1992), fault detection (Luo, 1995), earthquake (Jeng and Chang, 1998), control system design (Wong and Chen, 1998), structure failure (Liu, et al. 2001) and many examples (Liu et al., 25) have been conducted successfully.

In this paper an integrated AHP and grey models, namely AHP/GM, is proposed for building up a quantitative method for dynamic risk assessment and prediction of debris flow hazards. Three layers and nine influence factors (criteria) are involved in the structure of AHP. The relative judgment among each influence factor is built up based upon 9 scaling levels to form the reciprocal judgment matrices for evaluating weighting vectors for each layer. After the relative risk impact of each influence factor is obtained, grey models of GM(1,1) are employed for dynamic prediction of intensity of rainfall and accumulated rainfall, while linear model is for the duration of rainfall, after a selected base point. And finally the time-varying overall risk index can be obtained. Two schemes of prediction are proposed and tested, one is the Single-Step Prediction (SSP) and the other is the Recycling Point-wise Prediction (RPP). The proposed AHP/GM methods will be applied and verified using a practical case of disasters occurred in Tung-Men Village of Hua-Lian County in eastern Taiwan.

RELATIVE RISK INDICES OBTAINED USING AHP MODEL

The procedures to construct AHP model for risk assessment of debris flow hazards and to obtain relative risk indices had been studied by Huang (2014), Huang, et al. (2015). The basic procedures are as follows:

- Establish a hierarchical model
- Setup comparison matrices
- Calculate the relative weights and the maximal eigen-values
- Check the consistency
- Evaluate the final assessed risk index

The top of a hierarchical model is the goal to be achieved by AHP, shown in Figure 1. The second layer (criteria layer) refers to the proposed major categories of influence factors. Factors in the third layer (sub-criteria-layer) support the factors in the second layer.^a

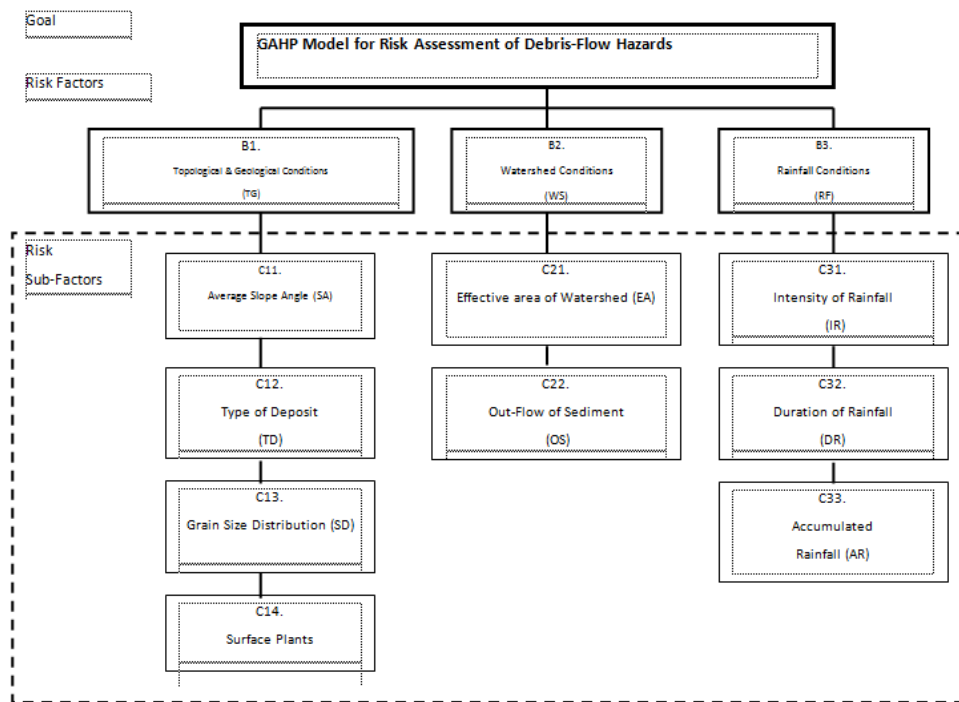


Figure 1: Hierarchical Model of the Risk Assessment of Debris-Flows Hazards Using AHP

Comparison matrices are obtained through filling in a questionnaire form by some experts in this field. Here we adopt 1-9 scaling method as suggested by Saaty (1980). The following judgment matrices are built up:

$$[B] = \begin{bmatrix} 1 & 2 & 1/2 \\ 1/2 & 1 & 1/4 \\ 2 & 4 & 1 \end{bmatrix}_{3 \times 3} \quad [C_1] = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 1/2 & 1 & 3/2 & 2 \\ 1/3 & 2/3 & 1 & 2 \\ 1/4 & 1/2 & 1/2 & 1 \end{bmatrix}_{4 \times 4} \quad [C_2] = \begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix}_{2 \times 2} \quad [C_3] = \begin{bmatrix} 1 & 1/2 & 1/3 \\ 2 & 1 & 2/3 \\ 3 & 3/2 & 1 \end{bmatrix}_{3 \times 3} \quad (1)$$

The calculated results of the *relative risk impact (RRI)* of each influence factors on the overall risk are:

$$\{RRI\} = \begin{bmatrix} 0.4774 & 0 & 0 \\ 0.2387 & 0 & 0 \\ 0.1761 & 0 & 0 \\ 0.1078 & 0 & 0 \\ 0 & 0.75 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 0.1667 \\ 0 & 0 & 0.3333 \\ 0 & 0 & 0.5 \end{bmatrix} \bullet \begin{bmatrix} 0.2857 \\ 0.1429 \\ 0.5714 \end{bmatrix} = \begin{bmatrix} 0.1364 \\ 0.0682 \\ 0.0503 \\ 0.0308 \\ 0.1071 \\ 0.0357 \\ 0.0952 \\ 0.1905 \\ 0.2857 \end{bmatrix} \quad (2)$$

DYNAMIC RISK ASSESSMENT AND PREDICTION BASED ON GM (1, 1) MODEL

Build up the Evaluation Criteria for Each Influence Factor

The evaluation value and criteria for debris-flow occurred in Taiwan is proposed as reported in Huang (2014), Huang, et al. (2015).

Identify Static and Dynamic Risk Influence Factors

In the AHP model we can find that 6 influence factors $C_{11}, C_{12}, \dots, C_{22}$ are nearly static and not vary with time significantly and we can consider these are static variables; while 3 influence factors C_{31}, C_{32} and C_{33} are inherently time-dependent. The linear mapping relationship between the quantities of dynamic influence factors and judgment vector components can be expressed as follows:

- **Intensity of rainfall (I) and E7 (C31)**

$$E_7 \quad (C_{31}) = \begin{cases} 1, & \text{for } I < 5 \text{ mm/hr} \\ 1 + \frac{9-1}{20-5}(I-5), & \text{for } 5 \text{ mm/hr} \leq I < 20 \text{ mm/hr} \\ 9, & \text{for } I \geq 20 \text{ mm/hr} \end{cases} \quad (3)$$

- **Duration (T) and E8 (C32)**

$$E_8 \quad (C_{32}) = \begin{cases} 1, & \text{for } T < 1 \text{ hr} \\ 1 + \frac{9-1}{20-1}(T-1), & \text{for } 1 \text{ hr} \leq T < 20 \text{ hr} \\ 9, & \text{for } T \geq 20 \text{ hr} \end{cases} \quad (4)$$

- **Accumulated rainfall (A) and E9 (C33)**

$$E_9 \quad (C_{33}) = \begin{cases} 1, & \text{for } A < 100 \text{ mm} \\ 1 + \frac{9-1}{400-100}(A-100), & \text{for } 100 \text{ mm} \leq A < 400 \text{ mm} \\ 9, & \text{for } A \geq 400 \text{ mm} \end{cases} \quad (5)$$

BUILD UP THE PREDICTION MODELS

Linear Predicting Model

Assuming we have original data set $x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(t_a)$ which is linearly varying such as the duration of rainfall (C32) in AHP of debris flow hazards, then the predicted sequences can be directly obtained using linear extrapolation as

$$x^{(0)}(t_a + p) = x^{(0)}(t_a) + m(p - t_a), \quad p = 1, 2, \dots, N_p \quad (6)$$

Where t_a is the time for activating prediction, N_p is the total number of points to be predicted; m is the linear slope of the line between $t = 1$ to $t = t_a$.

GM (1, 1)-Based Exponential Growth Predicting Model

When the original data set $x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(t_a)$ vary in a time-growing type, such as the intensity of rainfall (C31) and the accumulated rainfall (C33) in AHP of debris flow hazards, the GM(1,1) model can be employed for grey modeling and grey prediction. The basic procedures can be summarized as follows:

- **Obtain $\{x^{(1)}\}$ from $\{x^{(0)}\}$ using accumulated generating operation (AGO)**

$$x^{(1)}(k) = \sum_{m=1}^k x^{(0)}(m) \quad (7)$$

- **Obtain the mean sequences $\{z^{(1)}\}$**

$$z^{(1)}(k) = (x^{(1)}(k) + x^{(1)}(k-1))/2, \quad k = 2, 3, \dots, t_a \quad (8)$$

- **Calculate the Matrix $[B]$ and Vector $\{Y\}$**

$$[B] = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(t_a) & 1 \end{bmatrix}, \quad \{Y\} = \begin{Bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(t_a) \end{Bmatrix} \quad (9)$$

- **Calculate the parameter vector**

$$\begin{Bmatrix} a \\ b \end{Bmatrix} = ([B]^T [B])^{-1} [B]^T \{Y\} \quad (10)$$

- **Build up the GM(1,1) model for $\{\tilde{x}^{(1)}\}$**

$$\tilde{x}^{(1)}(k) = (x^{(0)}(1) - \frac{b}{a}) e^{-a(k-1)} + \frac{b}{a} \quad (11)$$

- **Obtain the whitening original set**

$$\tilde{x}^{(0)}(k) = \tilde{x}^{(1)}(k) - \tilde{x}^{(1)}(k-1) \quad (12)$$

- **Evaluate the predicted sequence $\tilde{x}^{(0)}(t_a + p)$**

(7a) Single-Step Prediction (SSP) Scheme: when this scheme is employed, the original data $\{x^{(0)}\}$ is employed for building the GM (1, 1) model and the predicted sequences are obtained at a time:

$$\tilde{x}^{(1)}(t_a + p) = (x^{(0)}(1) - \frac{b}{a}) e^{-a(t_a + p - 1)} + \frac{b}{a}, \quad p = 1, 2, \dots, N_p \quad (13)$$

$$\tilde{x}^{(0)}(t_a + p) = \tilde{x}^{(1)}(t_a + p) - \tilde{x}^{(1)}(t_a + p - 1), \quad p = 1, 2, \dots, N_p \quad (14)$$

(7b) Recycling Point-wise Prediction (RPP) Scheme: when this scheme is employed, initially we use the first $1 \sim N_a$ points to build GM (1, 1) model and predict only single point for $\tilde{x}^{(1)}(t_a + 1)$ and $\tilde{x}^{(0)}(t_a + 1)$; and in the 2nd cycle we use $2 \sim N_a + 1$ original data set to build a updated GM(1,1) model and predict only single point for $\tilde{x}^{(1)}(t_a + 2)$ and $\tilde{x}^{(0)}(t_a + 2)$, and continuously recycling the process to obtained all the predicted sequence $\tilde{x}^{(0)}(t_a + p)$, $p = 1, 2, \dots, N_p$.

$$\tilde{x}^{(1)}(t_a + m) = (x^{(0)}(m) - \frac{b}{a}) e^{-a(t_a + m - 1)} + \frac{b}{a}, \quad m = 1, 2, \dots, t_a \quad (15)$$

$$\tilde{x}^{(0)}(t_a + m) = \tilde{x}^{(1)}(t_a + m) - \tilde{x}^{(1)}(t_a + m - 1), \quad m = 1, 2, \dots, t_a \quad (16)$$

Since in each step one data point (old information) is updated and replaced by the newest data (new information) and this scheme is expected to be more precise than the SSP. This concept is similar to the rolling prediction employed in time-series problem.

Evaluate the Assessed Dynamic Overall Risk Index (ORI)

From the previous study on the risk assessment of debris flow hazards using AHP model (Huang (2014), Huang, et al. (2015)), the overall risk index can be evaluated as

$$ORI = \{RRI\}^T \bullet \{E\} = \sum_{i=1}^9 RRI_i \bullet E_i \quad (17)$$

Where $\{E\}$ is a 9×1 vector denoting the evaluation value of each influence factor (sub-criteria). We can extend this to dynamic assessment situation and write the equation in alternate form:

$$\{\hat{y}(t)\} = [C] \{x^{(0)}(t)\} \quad (18)$$

where $\{\hat{y}(t)\}$ denotes the output vector of the predicted Overall Risk Index (ORI), $[C]$ is the state-to-output transformation matrix containing the Relative Risk Impact (RRI), and $\{x^{(0)}(t)\}$ denotes the state vector describing the time variation of judgment vector E_i ($i = 1, 2, \dots, 9$).

APPLICATION OF AHP/GM QUANTITATIVE METHOD TO DYNAMIC RISK ASSESSMENT OF DEBRIS-FLOW HAZARDS

Description of Debris-Flow Disasters Occurred in Tung-Men Village

The case of debris-flow disaster we employed for checking the validity of risk assessment model is that occurred at June 23, 1990, in the Tung-Men Village, Sho-Lin Township, Hua-Lien County, Taiwan during the attack of Typhoon with strong storms. This debris-flow caused 24 houses fully destroyed, 11 houses almost destroyed, 29 deaths, 6 persons disappeared, 7 persons hurt. Yu (1990), Chao and Kuo (1991) conducted thorough investigations on this hazard. Furthermore, Shieh, et al (1992) reported field investigation on the disaster; Chen, et al. (1993) reported the material property of the deposit; Fang and Mau (1997) investigated the rainfall characteristics.

Recorded Data and Judgment Vector $\{E\}$

- **Static Data**

The judgment vector components for those static data (E_1, E_2, \dots, E_6) corresponding to the influence factors $(C_{11}, C_{12}, \dots, C_{22})$ are list in Table 1.

Table 1: Recorded Data of Investigation of Debris-Flow Hazards Occurred at Tung-Men

A. Risk Assessment Of Debris-flow Hazards	Recorded Data	Rank (1-9)
B1. Topological & Geological Conditions		
C11. Average Slope Angle(θ) (Degree)	36.4° (20°)	9
C12. Type of Deposit	Loose and crashed rocks	7
C13. Grain Size Distribution	Gravel content above 60% .pass 200# fine aggregate Below 14% .(GP-GM)	5
C14. Surface Plants	mainly artificial bamboo, shallow rooted	7
B2. Watershed Conditions		
C21. Effective Area of Watershed (m^2)	490000 m^2	9
C22. Out-Flow of Sediment (m^3)	56000 m^3	9

- **Dynamic Data**

Figure 2(a) shows the real record for the intensity of rainfall at Tung-Men Rainfall Measurement Station from 1:00 a.m., June 22, 1990 to 3:00 p.m., June 23, 1990, i.e., totally 27 hours (Shieh, et al.1992). And the duration and accumulated rainfall are expressed in Figure 2(c) and Figure 2(e), respectively. Based on the AHP model the judgment vector components $E_7(t)$, $E_8(t)$ and $E_9(t)$ corresponding to the influence factors (C_{31}, C_{32}, C_{33}) are shown in Figure 2(b), 2(d) and 2(f). It shows that intensity of rainfall varies significantly.

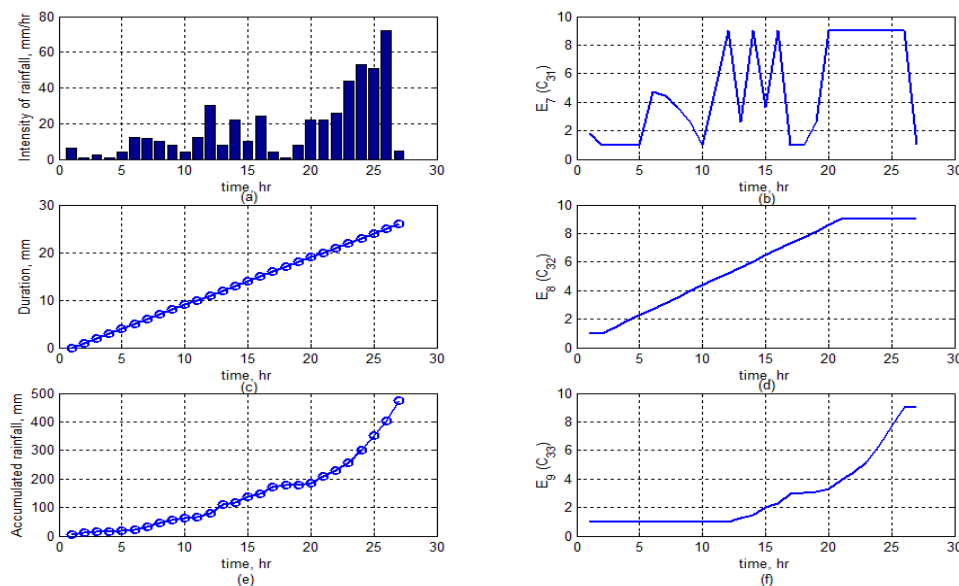


Figure 2: Original Data of Intensity of Rainfall, Duration and Accumulated Rainfall at Tung-Men Village and the Associated Judgment Vector Components $E_7(C_{31})$, $E_8(C_{32})$, And $E_9(C_{33})$ Before Disaster Occurrence

Dynamic Risk Assessment of Debris-Flow Hazard

We choose the data points from 1 to 15 for analysis ($N_a = 15$) and then predict the data from 16 to 27 ($N_p = 12$). The real temporal point of debris flow disaster is at the point between 26 and 27 (2:49 p.m., June 23, 1990). We expect to have earlier precaution of the hazard before the occurrence and thus to get more time for warning, alarming and

preparation of rescuing people. For practical implementation of alarming system, we assume to set the warning time at $ORI \geq 7$ and the alarming time at $ORI \geq 8$. (It can be adjusted according to practical requirement).

- **Single-Step Prediction (SSP) Scheme**

When the scheme is employed, the first 15 data of intensity of rainfall and accumulated rainfall to build GM (1,1) model to obtain the whitening data $\hat{x}^{(1)}(k)$, $k=1,2,\dots,N_a+N_p$ and the predicted original data set $\hat{x}^{(0)}(k)$, $k=1,2,\dots,N_a+N_p$ using Eq. (7~13); while the duration of rainfall is predicted using linear law, Eq. (6). The dashed lines in Figure (3a), (3c), and 3(e) are predicted using SSP schemes; while the corresponding judgment vector components $\hat{E}_7(t)$, $\hat{E}_8(t)$, and $\hat{E}_9(t)$ are shown in Figure 3(b), 3(d) and 3(f), respectively. It can be observed that the predicted intensity of rainfall and accumulated rainfall, as expected, grow exponentially with time. Figure 4 shows the final ORI prediction using SSP scheme in which the predicted curve is much deviated from the real one. However, using this SSP scheme we can have early precaution of the debris flow disaster (warning before 10 hours and alarming before 6 hours).

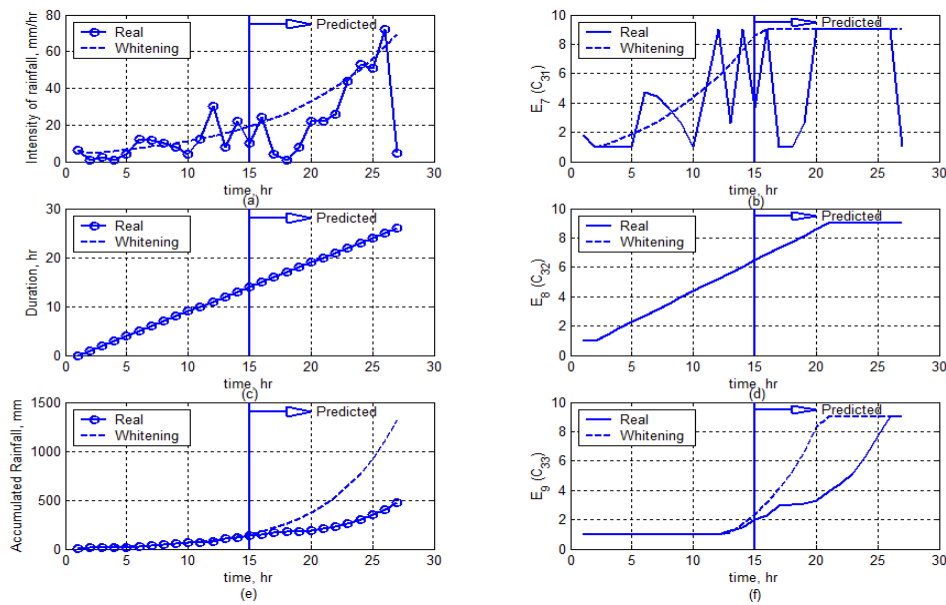


Figure 3: SSP Predicted Results of Intensity of Rainfall, Duration and Accumulated Rainfall at Tung-Men Village and the Associated Judgment Vector Components $E_7(C_{31})$, $E_8(C_{32})$, And $E_9(C_{33})$ Before Disaster Occurrence

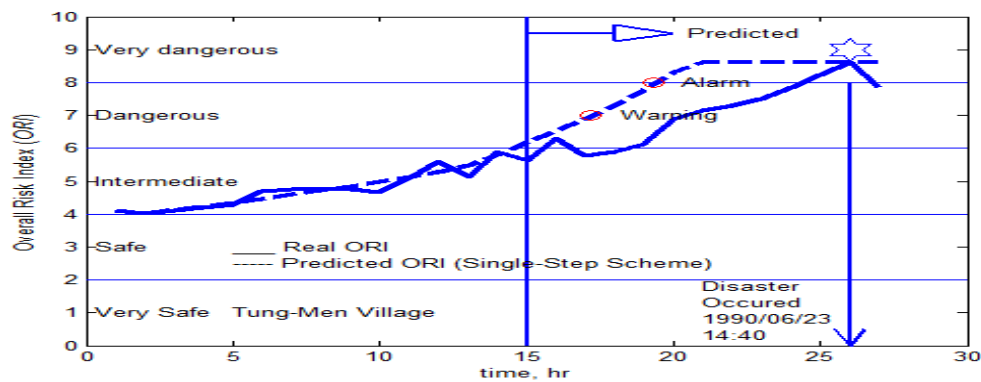


Figure 4: SSP Predicted Results of Overall Risk Index (ORI) at Tung-Men Village

- **Recycling Point-Wise Prediction (RPP) Scheme (Rolling Prediction Scheme)**

In this scheme the final points of data set in each cycle for GM (1, 1) analysis are updated by the new coming real data, the predicted results (dashed lines) for intensity of rainfall (Figure 5(a)), accumulated rainfall (Figure 5(e)) and their corresponding judgment vector components (Figure 5(b) and Figure 5(f)) are closer to the real results as compared with those in Figure 3 using SSP. The results are reasonable because only single data point is predicted in each cycle and always the newest data are employed for building the grey modeling. Furthermore, Figure 6 shows the final *ORI* prediction using RPP scheme in which the predicted curve is also closer to the real one than that in Figure 4 using SSP. However, we should notice that even it is more precise in the predicted time of occurrence but the time of earlier precaution would be sacrificed (warning before 7 hours and alarming before 2 hours).

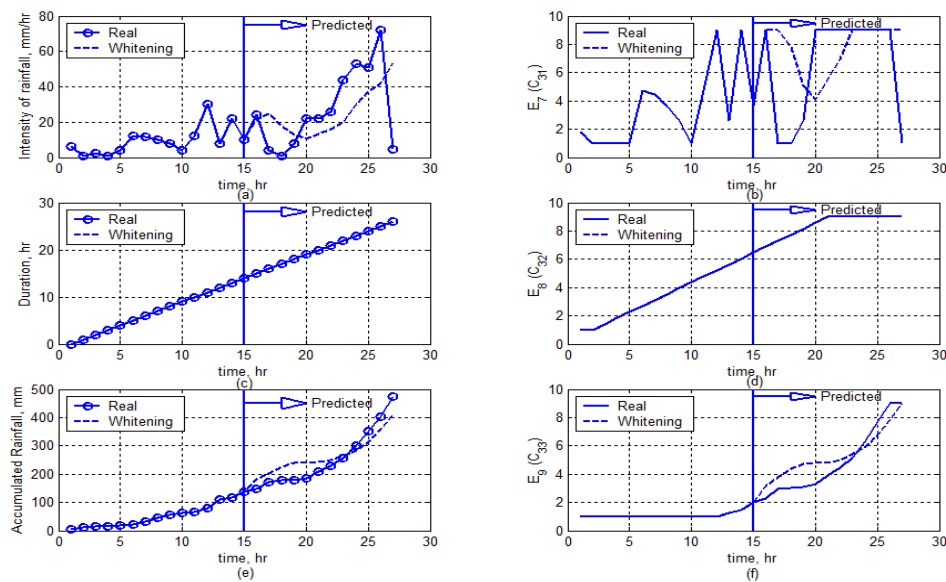


Figure 5: RPP Predicted Results of Intensity of Rainfall, Duration and Accumulated Rainfall at Tung-Men Village and the Associated Judgment Vector Components $E_7(C_{31})$, $E_8(C_{32})$, And $E_9(C_{33})$ Before Disaster Occurrence

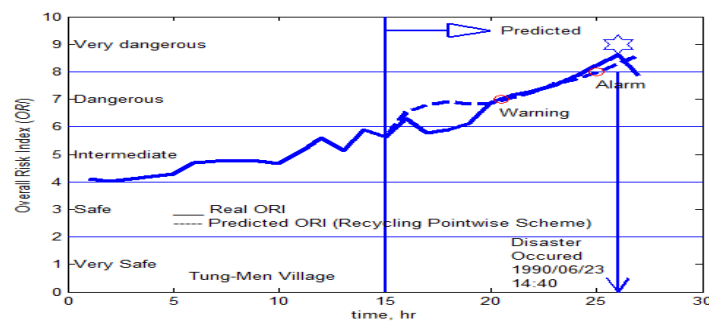


Figure 6: RPP Predicted Results of Overall Risk Index (ORI) at Tung-Men Village

CONCLUSIONS

An effective and efficient AHP/GM-based quantitative method for dynamic risk assessment and prediction of debris-flow hazards is presented and successfully verified using a practical recorded data of debris-flow disaster occurred in Tung-Men Village, Taiwan. In this approach, AHP is employed for building the hierarchical structure of influence factors and evaluate the relative risk impacts (*RR*) of influence factors; whereas the GM(1,1) models are employed for grey modeling the dynamic variation of intensity of rainfall as well as accumulated rainfall for dynamic risk prediction. Single-Step Prediction (SSP) scheme and Recycling Point-wise Prediction (RPP) scheme are proposed and compared with each other. The findings are:

- Integrated AHP and GM theory to build up an AHP/GM-based quantitative dynamic risk assessment and prediction method is for debris flow hazards including multiple influence factors is feasible. With this method the major influence factors can be constructed and ranked, the relative risk impact of each influence factors can be evaluated, and the overall risk index of debris-flow hazard can be obtained including static influence factors and dynamic ones which are predicted using GM (1, 1) models.
- SSP scheme provides a single cycle and convenient approach for dynamic risk prediction. In general long-term predicted results might deviate from the real values too much and thus over-estimation the risk potential. However, for practical implementation, SSP is expected to provide an early precaution of highly disaster hazards.
- RPP scheme provides more precise dynamic predicted results for the overall risk index than SSP scheme due to in this grey models newest data are added into the basic set for predicting only one new unknown data. For compromise of precaution and the precision requirement the predicted data points in RPP can be added to 2, 3 or more.

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